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The CYGNUS Collaboration

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Abstract

Using the cosmic ray shadows of the sun and moon, we have estimated the angular resolution of the CYGNUS extensive air shower array. With the event sample now available we estimate the angular resolution of the array to be $0.70^{+0.07}_{-0.06}$ degrees. The resolution depends on the total number of detected shower particles. A new parameterisation of the measured shower-front timing structure and the use of counters with small pulse areas lead to a ~25% improvement in the angular resolution. The systematic pointing error of the array is less than 0.4°.

1. INTRODUCTION

Searches for astrophysical point sources of ultra-high energy (UHE) gamma radiation must cope with a large background of cosmic rays. Rejection of this background may be accomplished by selecting events based on shower properties (i.e. muon content) and/or by improving the angular resolution of the detector. The minimum detectable gamma-ray flux is proportional to the angular resolution.

In this paper the angular resolution is defined as the standard deviation of a symmetric, 2-dimensional Gaussian point-spread function. It is well known that a round bin with a radius of 1.58 times the angular resolution of the detector maximises the significance of a signal for a large number of events. An angular bin that is larger or smaller than this tends to lower the significance of any signal.

Using the cosmic ray shadows of the sun and the moon it is possible to measure the angular resolution of an extensive air shower array (Clark 1957). We have previously reported a measurement of the angular resolution of the CYGNUS array using this technique (Alexandreas. *et al.* 1991a). Here we present an updated analysis of the angular resolution using a larger event sample. We examine the dependence of the angular resolution on individual air-shower characteristics. In addition we demonstrate that a new parameterisation of the shape of the shower front as sampled by the detector and the use of counters with small pulse areas lead to a ~25% improvement in the angular resolution.

2. THE CYGNUS EXPERIMENT

The CYGNUS air shower array, located in Los Alamos New Mexico, has been described elsewhere (Alexandreas, *et al.* 1992). This paper describes the analysis of ~300 million events taken between 1986 April and 1992 September. The CYGNUS-I array currently consists of 108 scintillation detectors deployed over 22,000 m^2. The event rate is ~3.5 Hz. For showers initiated by protons the most probable primary energy and the median primary energy detected by the array in its present configuration are approximately 50 TeV and 100 TeV, respectively.

This analysis makes use of ~250,000 events with arrival directions within ..5° of the center of the sun or moon.

3. ANGULAR RESOLUTION ESTIMATES

We have used the maximum likelihood method to estimate the angular resolution. We assume that the resolution function is a 2-dimensional Gaussian distribution with a constant standard deviation σ_r. This is used to compute the normalised probability of an event as a function of angular distance from the center of the sun or moon. The likelihood is the product of all the event probabilities and is computed numerically for many trial σ_r's. See Alexandreas *et al.* 1991a,b for a more detailed explanation of the procedure. We determine that the angular resolution of the array (σ_r) is $0.70^{+0.07}_{-0.06}$ degrees. This is smaller than (but consistent with) our previously reported result (Alexandreas, *et al.* 1991a).

By estimating σ_r for various subsets of the sun and moon data set, we have determined that σ_r is a strong function of *PSum*, the total number of detected particles (Figure 1) in the event. The pulse area measured in each detector has been normalised to that of a minimum-ionising, through-going particle. The dependence of σ_r on *PSum* was not evident in our earlier results due to an error in our sun and moon position programs.

4. ESTIMATION OF SYSTEMATIC POINTING ERRORS

We have determined the extent of possible systematic pointing errors by performing a maximum likelihood fit to the position of the sun and moon shadows in right ascension (α) and declination (δ). Analysis of the complete data set yields a combined shadow position offset from the true locations of the sun and moon of -0.09 ± 0.10 degrees in α and 0.06 ± 0.15 degrees in δ. Therefore, the systematic pointing error of the array is $< 0.4°$ at the 90% C.L..

5. IMPROVED ANGLE FITTING METHODS

Based on an examination of the measured time residuals with respect to the fitted shower plane, and on Monte Carlo simulations, we have determined an improved procedure for fitting the shower direction (Biller 1992). This procedure **1)** uses a new functional form to correct the relative arrival times in each counter for the curvature of the shower front, **2)** weights each counter in the directional fit according to the apparent width of the shower front as sampled by the scintillation detectors, and **3)** uses counters in the directional fits with pulse areas corresponding to ≥ 0.5 particles.

Applying this new procedure to the sun and moon data, a 25% improvement in σ_r is found (Figure 1 and Table 1). This improvement is also indicated by other techniques that are used to estimate the angular resolution. For example, the full array of counters is divided into two interleaved sub-arrays that are used to independently fit the direction of each shower. The space angle difference, Δ_θ, between the two directional fits is then computed (Alexandreas, *et al.* 1992). The median of the distribution of Δ_θ's is proportional to σ_r. The median values of the distributions of Δ_θ's listed in Table 1 also indicate a ~25% improvement in angular resolution compared to our original fitting algorithm. A detailed Monte Carlo simulation of the detector also supports this conclusion.

We estimate that approximately half of the improvement is from the use of additional counters with pulse areas corresponding to between 0.5 and 1.0 detected particle. The remainder of the improvement arises from the new parameterisation of the shape of the shower-front timing structure.

The significance of the combined sun and moon shadows (see Alexandreas, *et al.* 1991b) increases from 7.1σ to 8.9σ using the new parameterizations. When a parameterization of the dependence of σ_r on *PSum* (Figure 1) is applied, the significance increases to 10.5σ.

6. CONCLUSIONS

Using the shadows of the sun and the moon we have measured the angular resolution of the CYGNUS array to be 0.7°. This resolution is smaller (and better determined) than that previously measured with a smaller event sample. Therefore we have reduced the size of the angular bins used in searches for point sources of UHE gamma radiation (Alexandreas *et al.* 1993). In addition we have arrived at a new parameterization of the measured shower-front timing structure. This parameterization in conjunction with the use of counters with small pulse areas in the direction finding algorithm yields a ~25% improvement in angular resolution. We are in the process of incorporating this improvement in our analysis procedures.

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Fit Type	*PSum* Cut	N_{cut}	σ_r	Δ_θ	# Events
New	None	0.5	$0.52^{+.04}_{-.03}$	0.75	226,801
	< 100	0.5	$0.64^{+.07}_{-.06}$		153,574
	100-200	0.5	$0.39^{+.08}_{-}$[illegible]		41,146
	> 200	0.5	$0.40^{+.06}_{-.04}$		32,081
Old	None	1.0	$0.70^{+.07}_{-.06}$	1.00	234,643
	< 100	1.0	$0.83^{+.11}_{-.08}$		160,024
	100-200	1.0	$0.55^{+.10}_{-.09}$		42,024
	> 200	1.0	$0.39^{+.06}_{-.08}$		32,595
New	None	0.2	$0.58^{+.08}_{-.04}$	0.83	226,112
	None	0.5	$0.52^{+.04}_{-.03}$	0.75	226,801
	None	1.0	$0.58^{+.08}_{-.04}$	0.90	224,476

Table 1. Comparison of the angular resolutions derived from the shadows of the sun and moon using the old and the new parameterizations of the measured shower-front timing structure. N_{cut} is the minimum counter signal used in the fit, *PSum* is the sum of counter signals, and Δ_θ is the space angle difference between two sub-arrays (see text for explanantion).

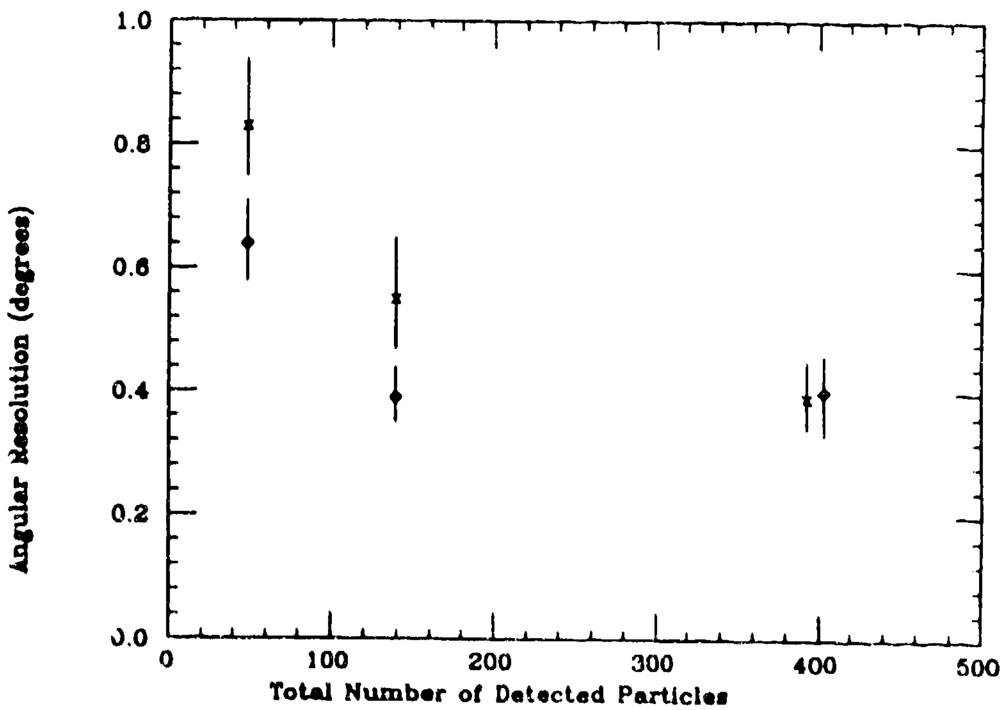

Figure 1: The angular resolution as a function of *PSum*. The X's (diamonds) correspond to the old (new) parameterisation of the shower-front timing structure.